Nano-powder coating can make fault surfaces smooth and shiny: implications for fault mechanics?

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Field and microstructural observations on exhumed, inactive, fault segments in plate margin systems show that most of the upper crustal slip occurs in zones with a thickness of less than a few tens of mm (Chester et al., 1993; Wibberley and Shimamoto, 2003). Slip zones in carbonate rocks show extreme slip localization within zones of less than a few hundreds of microns, commonly bounded by sharp principal slip surfaces which accommodate most seismic slip during earthquakes (De Paola et al., 2008; Fondriest et al., 2012; Smith et al., 2011).

Siman-Tov et al. (2013, p. 703 in this issue of *Geology*) observed that carbonate faults along the active Dead Sea Transform are characterized by naturally polished, reflective and glossy surfaces, termed fault mirrors (FMs). At the microscale, the FM slip zones consist of a <1 μm layer of tightly packed nanoscale grains, coating a thicker layer made of twinned and elongated μm-size calcite crystals, produced by plastic deformation. Siman-Tov et al. propose a ‘plastic-brittle’ mechanism to explain the formation of nanoparticles, whose nanosize is controlled by the “long” and “thin” beams of calcite crystals plastically deformed by twinning, and broken into nano-grains by brittle deformation. The nanograin layer localizes slip and deforms by bulk ductility. Other models proposed to produce nanograins rely on chemical-physical reactions triggered by frictional heating (De Paola et al., 2011; Han et al., 2010; Han et al., 2007) or shock-waves (Sammis and Ben-Zion, 2008), due to fast sliding during an earthquake. FMs have extremely smooth surface topography, with mean roughness of <100 nm for lateral scales below 550 nm (Siman-Tov et al., 2013). They are characterized by a Rayleigh roughness and a different structure at scales <1μm (Siman-Tov et al., 2013), compared to the self-affine roughness ranging from a few μm to km, as seen in studies on polished principal slip surfaces (Sagy et al., 2007). Siman-Tov et al. characterized the attributes and roughness of FM surfaces at the sub-μm scale, largely overlooked in previous studies, but critical in controlling the frictional behavior of faults.

The friction between sliding fault surfaces controls the initiation, propagation and termination of slip during earthquakes (Scholz, 1998). Leonardo Da Vinci first recognized that friction on the contact surface between sliding bodies is related to the ratio between the applied normal (F_n) and tangential shear (F_s) forces. Amontons (1699) observed that the friction between two sliding bodies does not depend on the macroscopic contact area, A, and that the shear force F_s is linearly proportional to the applied normal force, F_n, with the constant of proportionality, the sliding friction coefficient $\mu = F_s/F_n$ (Amontons' Law). The applied F_n is supported by a real contact area, A_r, made by a population of microcontacts (e.g., asperities), a small fraction of the macroscopic contactarea A (i.e., A_r <<A) (Bowden and Tabor, 1950). According to this adhesion theory, plastic yielding at asperities is expected as normal stresses approach the material yield strength. The effective shear strength of welded asperities must be overcome to slide. The main goal of adhesion theory is to develop a conceptual framework explaining

why macroscopic friction μ does not depend on the macroscopic contact area A, and why the macroscopic F_s is linearly proportional to the applied F_n (Scholz, 2002).

The conceptual framework of adhesion theory applies to the rate and state theory of friction, explaining the observed velocity and time dependence (Dieterich, 1979; Ruina, 1983), controlling the initiation of unstable sliding and earthquake nucleation, and mechanical healing of faults necessary to reset fault strength between failure events (Marone, 1998; Scholz, 1998). Static friction increases with the logarithm of time, interpreted as being due to the increase of contact area with contact age during interpenetration and creep of asperities, while contact size distribution is insensitive to time and normal stress (Dieterich and Kilgore, 1994). Sliding friction is velocity-dependent, and with a change in velocity evolves to new steady-state values over a finite critical slip distance, D_c (Dieterich, 1979; Ruina, 1983; Marone, 1998). D_c might be the slip necessary to renew a surface contact and scales with the sliding surface roughness (Marone, 1998). The conceptual framework of adhesion theory has been widely used to explain macroscale frictional behavior, but deviations from single asperity theories have sometimes been observed at the nanoscale, and attributed to the break-down of continuum mechanics (Mo et al., 2009; Szlufarska et al., 2008) or to changes in chemical bonding (Li et al., 2011). Whether asperity models can describe the behavior of contact asperities at the nano-scale becomes relevant to the case of natural principal slip surfaces with features similar to FMs (Siman-Tov et al., 2013).

Laboratory friction experiments under low slip rates (a few μm/s), displacements (<1 cm) and temperatures (T = 25 ºC) (Byerlee, 1978) and static borehole stress measurements in the brittle crust (Townend and Zoback, 2000) show that faults are usually strong (μ = 0.6–0.85; Byerlee's law). However, recent theoretical (Rice, 2006) and experimental studies (Di Toro et al., 2011) suggest that the coseismic frictional strength of faults is much lower (μ = 0.1–0.3) than predicted by Byerlee-type, low-velocity experiments, when slip velocities and displacements are ~ 1 m/s and a few m, respectively. Friction decreases with fault roughness for submicron size asperities, due to abrasion by brittle fracture (Byerlee, 1967). Thus, the smoothness of the slip surfaces could explain the weakening observed during friction experiments at seismic slip rates (~1 m/s), where reflective, glossy FMs-like slip surfaces were produced (Han et al., 2010; Han et al., 2007; Smith et al., 2013). Flash heating may be a viable mechanism for dynamic weakening in seismic faults on theoretical (Beeler et al., 2008; Rice, 2006) and experimental (Goldsby and Tullis, 2011) grounds. The operation of flash heating in natural seismic faults with FMs-like ultra-smooth nature (Siman-Tov et al., 2013) could be questioned, as unrealistically high slip rates would be required for surfaces with such nanoscale asperities (Han et al., 2010,2011; De Paola et al., 2011; Tisato et al., 2012).

Asperity sliding may occur by shearing through the interlocked asperities and large amount of wear are predicted and commonly observed along natural fault surfaces (Scholz, 2002). During recent friction experiments performed in granite rocks at sub- and seismic slip rates, fault lubrication has been observed when a critical gouge layer thickness is reached, and able to act as a "third body" type lubricant which separates the two sliding surfaces (Reches and Lockner, 2010). FM-like slip surfaces were also formed during friction experiments performed at seismic slip rates in carbonate rocks, when dramatic fault lubrication was also observed and interpreted as being due to the development of nano-powders of lime coating the sliding surfaces (Han et al., 2010).

Further experimental work performed at fast slip rates on nano-powders has shown that such materials can coat FM-like slip surfaces, making them very smooth; rounded nanoparticles can start rolling along them rather than sliding, switching from high sliding friction to low rolling friction (Han et al., 2011). However, nanopowder friction is strongly rate-dependent, as at low slip rates these materials display a high friction (Han et al., 2011); the role played by adhesion at low slip rates needs to be further investigated. The nano-powders coating the natural FMs slip surfaces (Siman-Tov et al., 2013) could act as a solid lubricant, in a similar fashion to what is observed in industry and inferred from FMs produced during friction experiments at seismic slip rates. Granular lubricants (particle size ~1 mm) consist of dry, cohesionless hard particles, and powder lubricants (particle size ~1 μm) of dry, cohesive, soft particles (Wornyoh et al., 2007). During sliding at low slip rates, granular particles undergo nearly elastic collisions and can slip, roll and collide with the surface, whereas powders undergo completely inelastic collision and can coalesce, producing a thin lubricating film protecting tribo-surfaces (Wornyoh et al., 2007). The frictional behavior of nano-powders at low and high seismic slip rates, however, is poorly understood and should be vigorously investigated, as they may hold the key to what controls the structure and frictional behavior of seismic fault zones (Siman-Tov et al., 2013).

Overall, Siman-Tov et al. will stimulate future studies of natural fault surfaces trying to understand the interplay between plastic/ductile and brittle deformation and its role in producing nanopowder coatings. It remains at present unclear whether FMs are unambiguous indicators of seismic slip. Future experimental work should be aimed at characterizing frictional properties and behaviors of nano-powders and smooth surfaces for a range of pressures, temperatures, pore fluid pressures, and slip rates typical of brittle crust faults. The challenge will be to bridge the gap between the mechanisms controlling the frictional behavior of faults at the macro-, micro-, and nano-scale.

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